

Impact of Stochastic Convection on Ensemble Forecasts of Tropical Cyclone Development

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ABSTRACT

Two versions of the Navy Operational Global Atmospheric Prediction System (NOGAPS) global ensemble, with and without a stochastic convection scheme, are compared regarding their performance in predicting the development and evolution of tropical cyclones. Forecasts of four typhoons, one tropical storm, and two selected nondeveloping tropical systems from The Observing System Research and Predictability Experiment (THORPEX) Pacific Asian Regional Campaign and Tropical Cyclone Structure 2008 (T-PARC/TCS-08) field program during August and September 2008 are evaluated. It is found that stochastic convection substantially increases the spread in ensemble storm tracks and in the vorticity and height fields in the vicinity of the storm. Stochastic convection also has an impact on the number of ensemble members predicting genesis. One day prior to the system being declared a tropical depression, on average, 31% of the ensemble members predict storm development when the ensemble includes initial perturbations only. When stochastic convection is included, this percentage increases to 50%, but the number of “false alarms” for two nondeveloping systems also increases. However, the increase in false alarms is smaller than the increase in correct development predictions, indicating that stochastic convection may have the potential for improving tropical cyclone forecasting.

1. Introduction

Forecasts of the genesis and evolution of tropical cyclones (TCs) remain a great challenge for numerical weather prediction, partially because of a lack of in situ observations over vast ocean areas and uncertainties in model physics parameterizations (Rogers et al. 2006). Ensemble forecasting adds a probabilistic component to the forecast, thus helping estimate forecast uncertainty. In addition to perturbing initial conditions to account for analysis uncertainty (e.g., Toth and Kalnay 1997; Wei et al. 2008; McLay et al. 2008), there is evidence that accounting for model uncertainty in ensemble design is important for TC forecasting (Puri et al. 2001; Goerss and Reynolds 2008). However, there has not been an

evaluation of the impact of stochastic physics on ensemble TC forecasts during the pregenesis phase.

During the months of August and September 2008, a multinational field campaign commenced in the western North Pacific tropical basin. Under the umbrella of The Observing System Research and Predictability Experiment (THORPEX) Pacific Asian Regional Campaign (T-PARC), the Tropical Cyclone Structure Program (TCS-08, sponsored by the U.S. Office of Naval Research) investigated the mechanisms and predictability of TC formation and development. In support of T-PARC/TCS-08, the Naval Research Laboratory (NRL) produced ensemble forecasts using the Navy Operational Global Atmospheric Prediction System (NOGAPS; Peng et al. 2004) based on the ensemble transform initial perturbation method (McLay et al. 2008). During the field program, it was noted that the NOGAPS ensemble appeared underdispersive (the observed track often was outside the envelope of ensemble tracks). This is consistent with the results of McLay et al. (2008), who found

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that the NOGAPS ensemble transform (ET) has initial perturbations that are too small in the tropics compared to the estimated analysis errors.¹ This is, in part, due to the neglect of model error in the ensemble formulation, which is expected to be more significant in the tropics than the midlatitudes. Reynolds et al. (2008) found that inclusion of stochastic convection in the ensemble design substantially increased the ensemble variance in the tropics. Thus, after the field phase, the ensembles were rerun with the addition of stochastic convection (Teixeira and Reynolds, 2008). The main objectives of this study are to examine whether the addition of stochastic convection results in larger ensemble track and intensity spread, and improved ensemble prediction of TC genesis and development through examination of several case studies from the TCS-08 time period.

2. Data and methods

a. Cases

Four typhoons (Nuri, Sinlaku, Hagupit, and Jangmi) that formed during T-PARC/TCS-08 compose the primary case studies in this paper. In addition, one tropical storm (Higos) was arbitrarily chosen for evaluation. Many nondeveloping tropical waves were observed in the basin during the field experiment. Two of these waves (TCS017 and TCS018 according to the naming convention during TCS-08) were chosen to be studied: one that was consistently weak and did not develop in numerical forecasts, and one that was slightly stronger and was considered by scientists during the field program to be a candidate for development based on numerical forecasts.

b. Description of NOGAPS ensemble forecasts

Two NOGAPS ensemble forecast systems are compared. The first one is performed with perturbed initial conditions (control ensemble or CTRL) generated by an ensemble transform method (McLay et al. 2008). The ensemble includes 32 NOGAPS forecasts from perturbed initial conditions and one forecast from the (truncated) unperturbed analysis produced by the NRL atmospheric variational data assimilation system (NAVDAS), all with T119 horizontal resolution and 30 vertical levels. A second NOGAPS ensemble includes a stochastic convection scheme (Teixeira and Reynolds 2008) in addition to the ensemble transform initial perturbations (STO).

The stochastic convection accounts for uncertainties in the subgrid-scale moist convective parameterization using probability density functions to constrain the random determination of future states.

c. Cyclone tracking method

The tropical systems are tracked in the ensemble forecasts generated during both the pregenesis and postgenesis phases. The TC *genesis time* is defined here as when the system is designated by the Joint Typhoon Warning Center (JTWC) as a tropical depression in the best-track data. We choose this time as a reference point because it serves as a clear dividing line between an open wave and closed circulation. Similar to Snyder et al. (2010), a manual tracking method using 850-hPa fields is employed for evaluation of model forecasts. The criteria to define the development (genesis) of tropical systems are as follows: 1) vorticity greater or equal to $7.5 \times 10^{-5} \text{ s}^{-1}$ and 2) two closed height contour lines within 5° at a 10-m interval. A closed circulation in the wind field is also used at the same time to help identify the vortex center [see details in Snyder et al. (2010)]. These criteria were compared with Cheung and Elsberry (2002), who tracked TC formations over the western North Pacific with the NOGAPS deterministic forecasts. Results show that the vorticity limit set here ensures TC development, as weak tropical disturbances rarely reach this intensity.

Each ensemble forecast initialized in the pregenesis phase is given one of four designations. “Genesis” is when the genesis criteria are met in the forecasts. A “vortexlike” designation is applied if the system has closed height contour lines, but the vorticity maximum does not reach the required intensity. This indicates that the forecast develops a system of some strength, but one that is weaker than genesis status. If genesis criteria are met but are not maintained for more than 48 h, the system is labeled as “dissipation.” If none of the criteria are met at any time in the forecast period, the forecast is designated as “nondevelopment.” A successful genesis forecast is defined if the aforementioned criteria in vorticity and height lines are satisfied within 12 h of the observed genesis event. Ensemble forecasts out to 120 h initialized from 0000 UTC are evaluated. Each investigation begins at least 60 h before tropical depression designation and continues at least 42 h after the system becomes a tropical depression. Performance is then compared between the ensemble forecasts with and without stochastic convection.

3. A case study: Typhoon Jangmi

Jangmi originated as an area of intense convection east of Guam on 16 September 2008. Intermittent and

¹ Increasing the size of the initial perturbations in the tropics does not sufficiently address this problem, as it results in small perturbation growth and initial perturbations to the TC vortices that are unrealistically large.

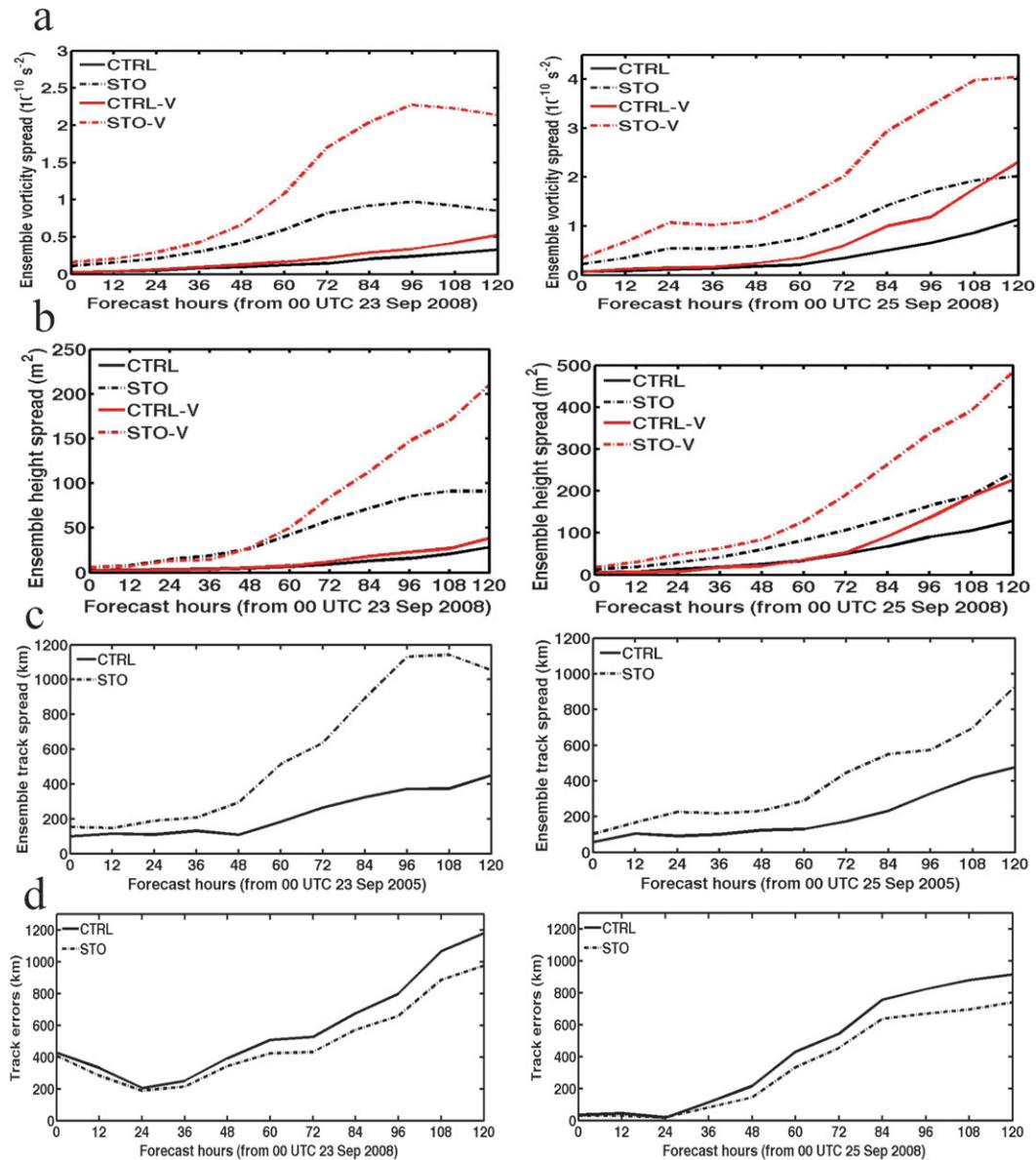


FIG. 1. Time evolution of ensemble spread for both CTRL (solid) and STO (dashed) averaged over 1) a box of 30° longitude by 20° latitude where Jangmi evolved (black curves) and 2) the vortex storm core regions of 5° longitude by 5° latitude around storm center positions (red curves) of (a) vorticity and (b) height at 850 hPa, with the spreads defined as the variance of ensemble members relative to the ensemble mean. (c) The time evolution of ensemble spread (standard deviation) of the track at the lead time 1 day (left) before (23 Sep) and (right) after (25 Sep) Jangmi's genesis. (d) The errors of the ensemble mean track forecasts are illustrated.

scattered convection continued through 23 September. The JTWC designated the system a tropical depression at 1800 UTC 23 September, followed by tropical storm status at 0000 UTC 24 September, typhoon status at 0600 UTC 25 September, and super typhoon status on 27 September. Since Jangmi was the most notable super typhoon during the 2008 season, we present a detailed evaluation of the cyclone tracking for this case.

The ensemble spread of intensity and track in the two sets of ensemble forecasts are compared in Fig. 1. The time evolution of the ensemble spread of vorticity (Fig. 1a) and height (Fig. 1b) over the storm center (averaged over 5° by 5° boxes centered on the storm positions, red curves), and in the environment of Jangmi (averaged over a box of 30° longitude by 20° latitude where Jangmi evolved, black curves) for forecasts starting the day

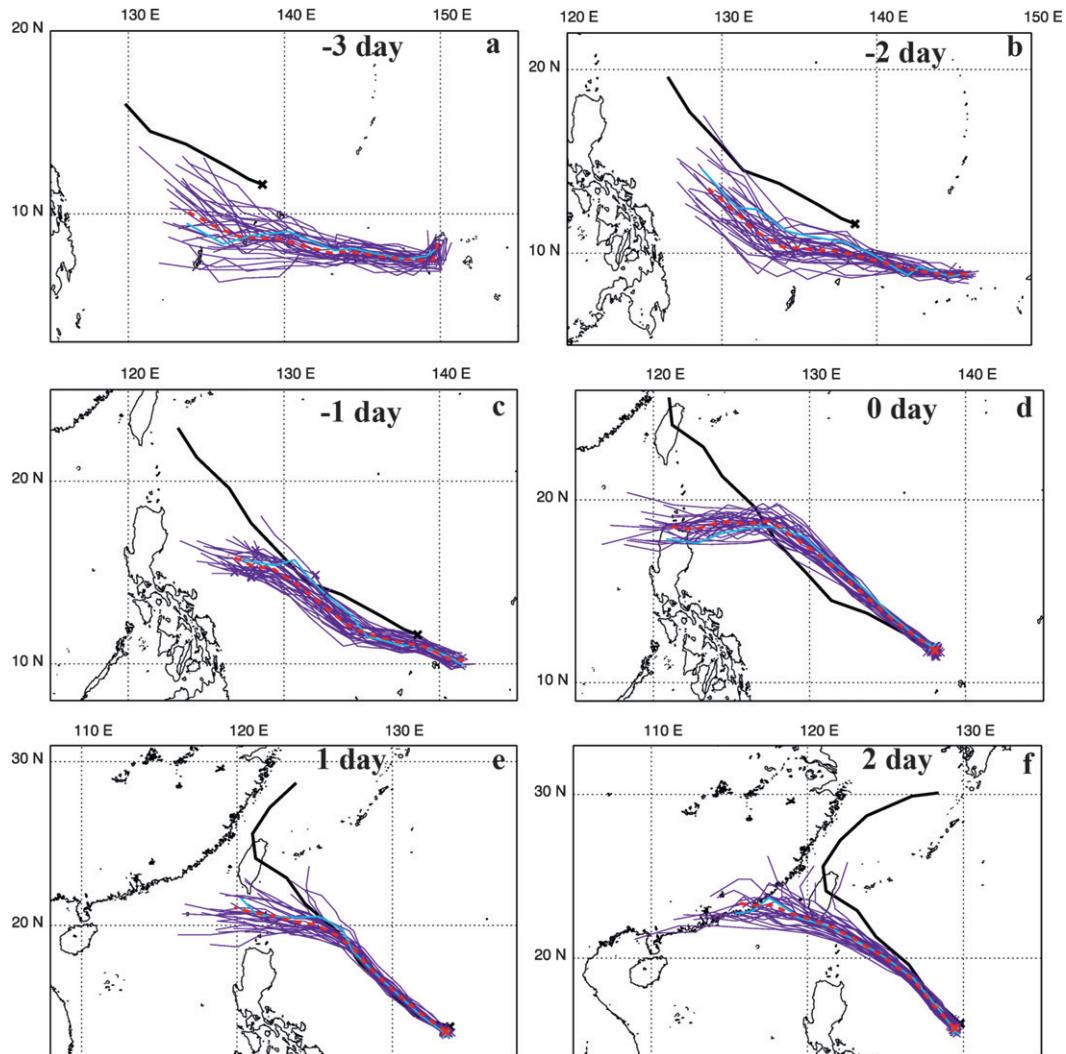


FIG. 2. The tracks of 0–120-h CTRL ensemble forecast for Typhoon Jangmi (purple thin lines) from 0000 UTC 21 Sep–26 Sep 2008 (corresponding to Figs. 2a–f, respectively), compared with the corresponding NOGAPS deterministic forecast, i.e., “member 0” (blue line), and JTWC best track (thick black line). Red dashed lines denote the ensemble mean. An “x” designates (a)–(c) the forecasted genesis (for lead time –3 to –1 day) and (d)–(f) the TCs that met the genesis criteria.

before (left panel) and after (right panel) Jangmi’s genesis. It is clear that, with the addition of stochastic convection, the ensemble spread in storm intensity and the large-scale environmental fields increases. In addition, the ensemble track spread is increased (Fig. 1c) and the accuracy of the ensemble mean track forecasts is improved with stochastic convection (Fig. 1d).

To illustrate further details of the impact of stochastic convection on track and genesis forecasts, Figs. 2 and 3 show the tracks and TC genesis from the ensemble forecasts, ensemble mean track, and the JTWC best track for CTRL and STO. These figures illustrate larger spread in ensemble tracks in STO compared with CTRL. In

addition, the observed track is also more often contained within the envelope of ensemble member tracks with the addition of stochastic convection. Regarding the prediction of genesis, for CTRL, none of the ensemble members predict genesis at 3- and 2-day lead times (Figs. 2a,b), but 12 members predict genesis at the 1-day lead time (Fig. 2c). In contrast, STO has a much higher fraction of ensemble members predicting genesis for Jangmi. For the forecasts initiated on 21 and 22 September 2008, 7 and 8 STO members predict the genesis of Jangmi (Figs. 3a,b), compared to none of the CTRL members. In addition, a few STO members clearly predict recurvature of Jangmi from the forecasts

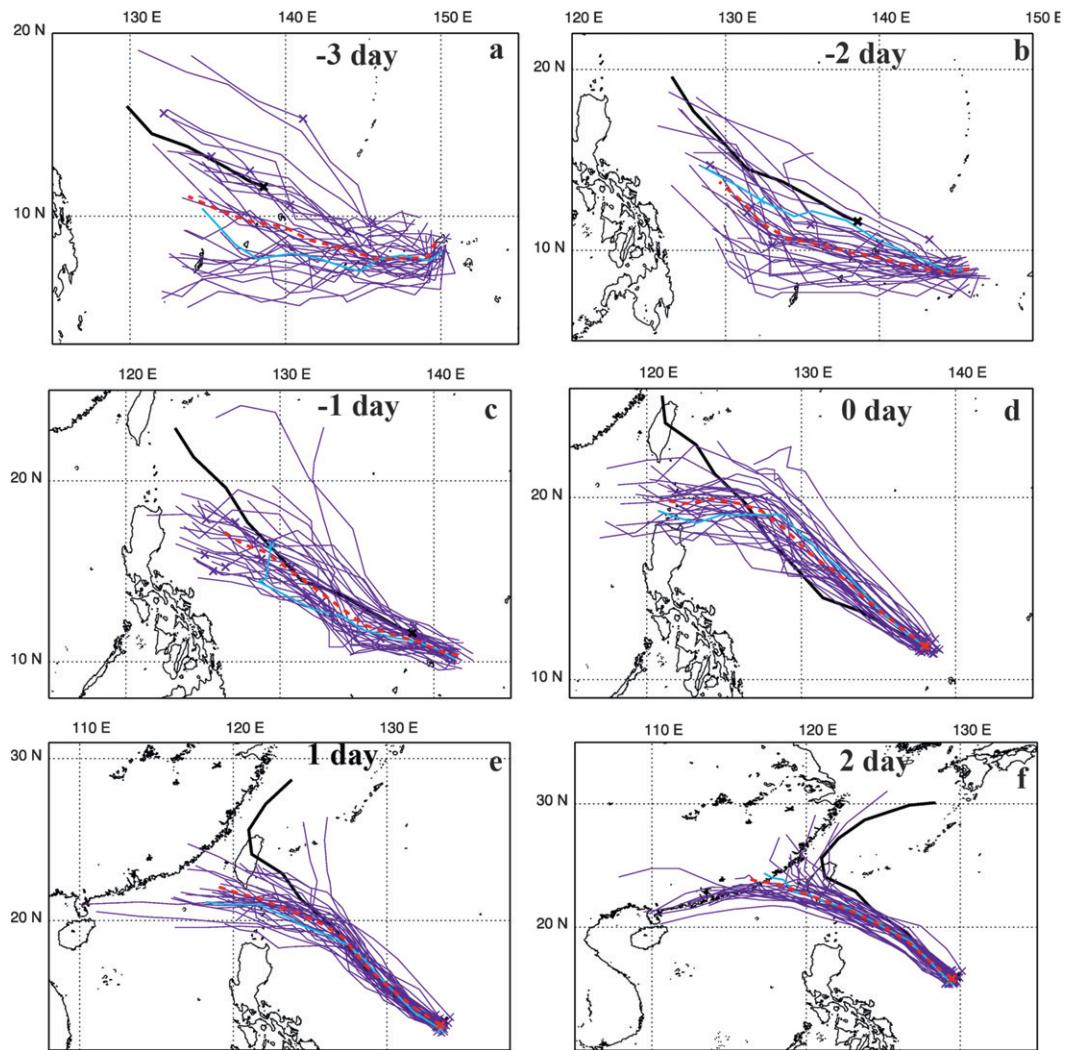


FIG. 3. As in Fig. 2, but for STO ensemble forecasts at 0000 UTC (a) 21 Sep, (b) 22 Sep, (c) 23 Sep, (d) 24 Sep, (e) 25 Sep, and (f) 26 Sep 2008.

initialized on 25 and 26 September (Figs. 3e,f), while almost none of the members in CTRL indicate a clear recurvature of Typhoon Jangmi.

4. Evaluation results from all cases

To reach more general conclusions, evaluations are performed for the other cases (both developing and nondeveloping) mentioned above. Table 1 summarizes the evaluation results. Note that at lead times of +1 and +2 days after genesis is observed, all of the ensemble member forecasts meet the genesis criteria, supporting the appropriateness of the genesis criteria used. In addition, most ensemble forecasts meet the genesis criteria on the day that genesis occurs (note, in some instances, such as Hagupit and Higos, the storm officially reached

tropical depression status after the 0000 UTC analysis time). With the emphasis on the forecast of genesis, the discussion hereafter focuses on the three lead times in the pregenesis phase only.

CTRL has low probabilities of genesis (percentages of ensemble members forecasting genesis). Averaged over all three pregenesis lead times for each cyclone, the probability of genesis does not exceed 40% for any individual case. The genesis rate is just under 20% when averaged for all cases and lead times. If one combines genesis and vortexlike cases as a metric for genesis prediction, the numbers increase somewhat. Nuri, Hagupit, and Higos all surpass the 50% mark, with Higos surging to near 75%. However, Sinlaku and Jangmi only increase marginally, and both still fail to reach a 25% rate of probability.

TABLE 1. Predictions of each cyclone for different lead times relative to the system being designated a tropical depression by JTWC. Values represent number of members (out of 32 ensemble members plus NOGAPS deterministic forecast) predicting genesis (*G*), vortexlike development (*V*), premature dissipation (*D*), and nondevelopment (*N*). Tracking results from CTRL and STO are shown separately.

Lead time (approx days)	Nuri		Sinlaku		Hagupit		Jangmi		Higos	
	CTRL	STO								
	<i>G/V/D/N</i>									
-3	0/1/0/32	3/2/0/28	0/9/0/24	1/2/0/30	22/7/2/2	30/2/0/1	0/0/0/33	7/3/0/23	0/0/0/33	2/4/1/26
-2	4/18/0/11	4/3/0/26	1/0/0/32	3/4/0/26	10/7/4/12	22/4/0/7	0/3/0/30	8/2/0/23	8/25/0/0	17/12/0/4
-1	33/0/0/0	25/6/0/2	1/1/0/31	11/4/0/18	4/5/1/23	10/6/0/17	12/9/0/12	18/2/0/13	1/31/0/1	19/10/0/4
0	33/0/0/0	31/0/2/0	33/0/0/0	33/0/0/0	33/0/0/0	28/2/2/1	33/0/0/0	30/3/0/0	23/10/0/0	26/7/0/0
1	33/0/0/0	33/0/0/0	33/0/0/0	33/0/0/0	33/0/0/0	33/0/0/0	33/0/0/0	33/0/0/0	33/0/0/0	33/0/0/0
2	33/0/0/0	33/0/0/0	33/0/0/0	33/0/0/0	33/0/0/0	33/0/0/0	33/0/0/0	33/0/0/0	33/0/0/0	33/0/0/0

If the ensembles show some promise for predicting genesis and are not just reflecting some climatological genesis occurrence rate in the forecasts, one would expect the probability of genesis to increase as lead time decreases. The results as a function of lead time are summarized in Table 2. The probability of genesis does indeed increase as lead time decreases when averaged over all cases, although the forecasts from 2- and 1-day lead time of Hagupit present exceptions in this regard (Table 1), perhaps as a result of poor initial analyses.

Overall, the genesis rates are still low in CTRL, starting with 13% at 3-days lead time, increasing to 31% at 1-day lead time. Combining genesis and vortexlike criteria, the 2-day lead time rates increase to 46%, while the 1-day lead time surpasses 50%. In contrast, STO shows a larger fraction of ensemble members predicting genesis. This fact is readily apparent in the overall genesis percentage (totaled for all cyclones and all lead times): 36% compared to 20% for CTRL.

Systems tend to be stronger in STO than in CTRL, both on average and on a case-by-case basis. For example, for Higos, CTRL has double the number of vortexlike cases as genesis cases, while STO has double the number of genesis cases as vortexlike cases (Table 1). STO has many ensemble members that predict Higos to intensify, and some even exceed the observed strength of Higos. Averaged for all TCs, STO forecasts have higher probability of genesis than CTRL for all lead times (Table 2), ranging from 26% for the 3-day lead time to 50% for the 1-day lead time. The differences between STO and CTRL are more pronounced for genesis-only than for genesis plus vortexlike criteria.

Overall, STO has a higher prediction rate of genesis than CTRL, but it may also lead to a higher false alarm rate. To investigate this, the ensemble predictions of genesis in two nondeveloping cases are also examined. The contingency table (Table 3) shows that the fraction of ensemble members predicting genesis for the cases in which genesis is not observed is far smaller than for the

cases in which it is observed. For CTRL, 4 ensemble members predict genesis for the nondeveloping cases out of a total of 264 (which results in a probability of genesis of 1.5%), compared with 96 members predicting genesis for the developing cases, out of a total of 495 (19.4%). Both numbers are higher for STO (25 out of 264 for the nondeveloping cases or 9.5%, and 180 out of 495 or 36.4% for the developing cases). While both the probability of genesis and false alarm rate increase when stochastic convection is included in the ensemble, the total number of correct forecasts is higher in STO (419) than in CTRL (356). It should be noted, however, that consideration of all nondevelopers in the western Pacific basin during this season may well increase the number of false alarms.

5. Conclusions

In this paper, the NOGAPS ensemble forecasts with and without stochastic convection are evaluated in their ability to predict the genesis of TCs. The primary motivation behind including stochastic convection in the ensemble is to incorporate model uncertainty due to the convective parameterization into the ensemble design and thereby increase the ensemble spread in the tropics. It succeeds in this respect, as shown in Figs. 1–3. In nearly

TABLE 2. Probability of genesis in the ensembles for each lead time in CTRL and STO, combined for all five named cyclones.

Lead time (days relative to genesis)		Genesis (<i>G</i>)	Vortexlike (<i>V</i>)	<i>G</i> + <i>V</i>	Nondevelop (<i>N</i> + <i>D</i>)
-3	CTRL	13%	11%	24%	76%
	STO	26%	8%	34%	66%
-2	CTRL	14%	32%	46%	54%
	STO	33%	15%	48%	52%
-1	CTRL	31%	28%	59%	41%
	STO	50%	17%	67%	33%

TABLE 3. Number of ensemble forecasts either predicting genesis or not predicting genesis for the five cases (three lead times) in which genesis was observed, and for the two cases (four forecasts each) in which genesis was not observed. The results for the CTRL ensemble are given first, followed by the results for the STO ensemble in parentheses. The total number of ensemble forecasts for the observed genesis cases is 33 ensemble members \times 5 cases \times 3 lead times = 495. Total number of ensemble members in which genesis was not observed is 33 ensemble members \times 2 cases \times 4 forecasts = 264.

	Genesis cases: CTRL (STO)	Nondevelopment cases: CTRL (STO)
Predict genesis	96 (180)	4 (25)
Do not predict genesis	399 (315)	260 (239)

all of the cases, the stochastic ensemble has increased track spread over the control ensemble. The ensemble mean tracks are more accurate in the ensemble forecasts with stochastic convection. These results are consistent with the conclusions from Puri et al. (2001), who found that stochastic forcing increased the spread in intensity of tropical cyclones, and the general findings by Teixeira and Reynolds (2008) and Reynolds et al. (2008), who show that inclusion of stochastic convection substantially enhanced ensemble spread of the tropical winds.

The addition of stochastic convection increases the fraction of ensemble members predicting genesis in the developing cases (Table 2). Meanwhile, it also increases the number of “false alarms” in two nondeveloping cases. However, in this limited sample, the increase in correct genesis predictions is greater than the increase in false alarms. While the small sample size precludes statistically significant results, these preliminary findings indicate promise for stochastic convection in improving ensemble forecasts of genesis. Additional investigation is needed with a larger sample size and the inclusion of more nondevelopers in order to draw more concrete conclusions on the advantages of stochastic convection.

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